Mental Models

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Abstract

People construct small-scale models of reality to understand the world and descriptions of it. Their iconic mental representations capture structural aspects of the elements simulated. They think about alternative possibilities that are consistent with assertions that contain logical connectives such as "if" and "or," quantifiers such as "all" or "some," and relational terms such as "in front of" or "before." They reason and make decisions by combining mental models, and they search for counterexamples to their conclusions. People construct mental models when they make deductive inferences and when they make inferences about probability and risk, as well as when they form concepts, solve problems, make moral judgments, or create alternatives to reality in their counterfactual thoughts.

INTRODUCTION

Mental models are mental representations in the mind of real or imagined states of affairs (Johnson-Laird, 1983). Mental models are "small-scale models" of reality (Craik, 1943); they underlie visual images and they may be similar to "pictures" (Wittgenstein, 1922); and they can also be "iconic" representations that capture structural aspects of the elements simulated (Johnson-Laird, 2006). Hence, mental models are akin to architects' models or physicists' diagrams.

The theory of mental models has been experimentally tested and computationally simulated to explain how people understand and reason deductively with assertions that contain propositional connectives such as "if," "or," and "not," as well as syllogisms based on quantifiers such as "all" or "some" and inferences based on relational terms such as "in front of" or "before" (Johnson-Laird & Byrne, 1991). It explains how people detect inconsistencies and construct explanations; it has led to the discovery of a new set of illusory inferences; and it has been extended to explain how people make inferences about probability and risk. It accounts for how people form concepts, solve problems, make moral judgments, and create alternatives to reality in their counterfactual thoughts (Byrne, 2005; Johnson-Laird, 2006).

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FOUNDATIONAL RESEARCH

When people understand an assertion about the relation of objects, such as "the knife is on the right of the fork, and the napkin is on the left of the knife," they construct a mental model of the spatial arrangement of the objects,

Napkin Fork Knife

(Byrne & Johnson-Laird, 1989; Jahn, Knauff, & Johnson-Laird, 2007). They construct similar mental models for many other sorts of relations (Goodwin & Johnson-Laird, 2005, 2008), including temporal relations (Schaeken, Johnson-Laird, & d'Ydewalle, 1996). Likewise, when they understand a quantified assertion such as "All of the napkins are blue," they envisage napkins that are blue (and they may also consider that there could be blue things that are not napkins):

napkin blue
napkin blue
napkin blue
blue

Each row in the diagram denotes a representation of the properties of an individual object (Johnson-Laird & Bara, 1984; Khemlani & Johnson-Laird, 2012). When they understand a conditional assertion "if there's a lily in the vase then there's a rose," they initially think about a single possibility corresponding to the way the world would be if the assertion were true, "There is a lily in the vase and there is a rose" (Johnson-Laird & Byrne, 2002):

lily rose

Their initial mental model contains some information that is represented explicitly, and other information that is implicit but can be "fleshed out" to be explicit if need be (Johnson-Laird, Byrne, & Schaeken, 1992; Khemlani, Orenes, & Johnson-Laird, 2012).

Principles of Parsimony and Truth

The possibilities people think about at the outset are guided by a principle of parsimony because of the limitations of human working memory (Barrouillet, Gauffroy, & Lecas, 2008; Johnson-Laird *et al*., 1992). Fast heuristic processes drive the construction of initial mental representations (Johnson-Laird, 1983). For example, the initial interpretation of the conditional differs from a

simple conjunction because people make a "mental note" that there may be alternative possibilities, which they have yet to think about:

lily rose
…

Alternative possibilities are captured in the diagram by separate lines, and the ellipsis denotes an implicit model (Johnson-Laird & Byrne, 1991).

People can also engage deliberative analytic processes to think about the alternative possibilities, if need be. The possibilities they consider are guided by a principle of truth and so they do not tend to imagine the false possibilities ruled out by an assertion. For example, they do not think about the false possibility, "there is a lily in the vase and there is no rose" (Espino, Santamaria, & Byrne, 2009; Johnson-Laird & Byrne, 2002). They can imagine various alternative possibilities that are consistent with an assertion. For example, for the assertion, "the knife is on the right of the fork, and the napkin is on the left of the knife," they can entertain alternative models:

Napkin Fork Knife
Fork Napkin Knife

Similarly for the conditional, "if there's a lily in the vase then there's a rose," they can think about alternative true possibilities, "There is a lily in the vase and there is a rose," and "There is no lily and there is no rose":

Lily Rose
No lily No rose

The mental representations can contain symbols to represent negation (Johnson-Laird *et al*., 1992). Considering alternative possibilities is an important step in the development of reasoning (Gauffroy & Barrouillet, 2011), and the alternative possibility people envisage most readily depends on task demands (Jahn *et al*., 2007).

Deductive Reasoning

People make inferences by constructing and combining mental models. They can reach conclusions that are possibly true—consistent with some of their models; or conclusions that are necessarily true—consistent with all of their models (Bell & Johnson-Laird, 1998), and they can detect inconsistencies (Johnson-Laird, Legrenzi, Girotto, & Legrenzi, 2000; Johnson-Laird, Lotstein, & Byrne, 2012). They reject a conclusion as a valid deduction if they find a

counterexample, that is, a possibility in which the premises hold, but the conclusion does not (Johnson-Laird & Hasson, 2003). For example, if they understand the assertion "the knife is on the right of the fork, and the napkin is on the left of the knife" by thinking about the possibility:

Napkin Fork Knife

they conclude "the fork is on the right of the napkin." But they reject the conclusion if they also construct the alternative possibility:

Fork Napkin Knife

Some inferences are guided by implicit heuristic processes, such as an inspection of an initial possibility, for example, the *modus ponens* inference: "if there is a lily then there is a rose. There is a lily. Therefore, there is a rose." It can be made on the basis of the initial possibility, "there is a lily and there is a rose" (Reverberi, Pischedda, Burigo, & Cherubini, 2012). Other inferences are guided by effortful deliberative processes, such as the systematic construction and combination of alternative possibilities, for example, the *modus tollens* inference "if there is a lily then there is a rose. There is no rose. Therefore there is no lily." Many reasoners say that nothing follows (Johnson-Laird & Byrne, 1991). However, if they "flesh out" their models to be more explicit, they can think about an alternative true possibility for the conditional: "there is no lily and there is no rose" and they can identify a shared common element. The more models that reasoners must entertain, the more difficult it is to reason correctly (Johnson-Laird *et al*., 1992). For example, the *modus tollens* inference is made more readily from a biconditional relation (which requires two possibilities to be considered) compared to a conditional relation (which requires three possibilities).

Computer simulations of the theory have tested its coherence in distinct domains such as propositional inference (Johnson-Laird & Byrne, 1991). A recent computer program provides a unified simulation of syllogistic, propositional, relational, and probabilistic inferences (see the *mReasoner* program at http://mentalmodels.princeton.edu/models/).

CUTTING-EDGE RESEARCH

The model theory of reasoning has been extended to explain how people think and reason in different domains. Mental models represent the intension or meaning of an assertion as well as its extension or the situations to which it refers, and extensional probabilities can be calculated over mental models to account for probabilistic inference and risk judgments (Khemlani, Lotstein, & Johnson-Laird, 2012; McCloy, Byrne, & Johnson-Laird, 2010).

The nature of the possibilities that people consider explains how they form concepts (Goodwin & Johnson-Laird, 2013) and solve insight problems (Lee & Johnson-Laird, 2013; Murray & Byrne, 2013). It has led to the discovery of a new set of illusory inferences (Johnson-Laird & Savary, 1999), and it explains how people construct explanations (Khemlani & Johnson-Laird, 2012) and make moral judgments (Bucciarelli, Khemlani, & Johnson-Laird, 2008). Three examples illustrate recent advances: how semantic and pragmatic factors affect the mental models that people construct, the brain regions implicated in searching for counterexamples, and the use of models in counterfactual reasoning.

Modulation of Models by Knowledge

Content and context modulate the possibilities that people consider (Johnson-Laird & Byrne, 2002; Quelhas, Johnson-Laird, & Juhos, 2010). For example, people judge a "strong" causal relation, "if the gong is hit then it makes a sound" to be consistent with two possibilities "the gong is hit and it makes a sound" and "the gong is not hit and it does not make a sound," akin to a "bi-conditional" relation (De Neys, Schaeken, & d'Ydewalle, 2005a; Goldvarg & Johnson-Laird, 2001). In contrast, they judge a "weak" cause, "if the fruit is ripe then it falls from the tree" to be consistent with three possibilities, "the fruit is ripe and it falls from the tree," "the fruit is not ripe and it does not fall from the tree," and crucially, "the fruit is not ripe and it falls from the tree," akin to a "conditional" relation. People think about the other causes that can also bring about the effect, and they retrieve an alternative cause, for example, "the fruit is not ripe and it falls from the tree, because it is a windy day" (De Neys, Schaeken, & d'Ydewalle, 2003; Frosch & Johnson-Laird, 2011).

In contrast, they judge an "enabling" causal relation (or an "allowing" relation), "If the product is advertised, then sales increase," to be consistent with a different set of possibilities, "the product is advertised and sales increase," "the product is not advertised and sales do not increase," and crucially, "the product is advertised and sales do not increase." They think about the other conditions that must also be present to bring about the effect, and they retrieve a disabling condition, "the product is advertised and sales do not increase, because the ads were not well-placed." They list these different possibilities when they are given the different sorts of causes (Goldvarg & Johnson-Laird, 2001) and they are "primed" to read these possibilities fast (Frosch & Byrne, 2012). On the mental model theory, inferences are never valid in virtue of their form alone, but take account of content and context (Johnson-Laird & Byrne, 2002). Consider the causal claim that overeating causes indigestion. Granted its truth, if it was observed

that Phil did not have indigestion, it could be inferred that he had not overeaten. But suppose that Phil had made an intervention: he took a pill that prevented indigestion. It would no longer be inferred from his lack of indigestion that he had not eaten too much. His intervention initiates a new causal chain that negates the effects of overeating. An intervention is sometimes said to have its own special logic (Sloman & Lagnado, 2005), but no special logic is required, just the ability to understand the premises:

Overeating causes indigestion.
Taking an indigestion pill prevents indigestion.

and to realize, as in the case of modulation, that the second premise takes precedence over the first (Frosch & Johnson-Laird, 2011; Johnson-Laird, 2006).

Counterexamples

Counterexamples suppress the inferences people make, for example, when they retrieve alternatives or disablers (Byrne, 1989a, 1989b; Byrne, Espino, & Santamaria, 1999). When people retrieve a disabler, for example, "the ads were not well placed" it suppresses their tendency to make the *modus ponens* inference, for example, "If the product is advertised, then sales increase. The product was advertised. Therefore, sales increased" (Byrne, 1989a; Schroyens, Schaeken, & Handley, 2003; Verschueren, Schaeken, & d'Ydewalle, 2005). Their ability to retrieve counterexamples depends on their working memory: it can be interrupted by secondary tasks that compete for working memory resources, and individuals with higher working memory capacity are better at retrieving, and at inhibiting, counterexamples (De Neys, 2011; De Neys, Schaeken, & d'Ydewalle, 2005b). Counterexamples affect the inferences people make when they are asked whether a conclusion logically follows from the premises, but not when they calculate the likelihood of the conclusion (Geiger & Oberauer, 2007; Markovits, Lortie Forgues, & Brunet, 2010).

There is greater activation in some regions of the brain when people make logical inferences that require counterexamples. When they construct a mental model during premise processing, for example, "V is to the left of X," there is activation primarily in the occipito-temporal structures; when they combine mental models, during the integration of premises, for example, "V is to the left of X, X is to the left of Z," there is activation primarily in the anterior prefrontal cortex; and when people search for counterexamples during the validation phase, for example, "V is to the left of X, X is to the left of Z, is V to the left of Z?," there is activation primarily in the posterior parietal

and prefrontal cortex (Fangmeier, Knauff, Ruff, & Sloutsky, 2006). Inferences that require counterexamples activate the right frontal pole in the prefrontal cortex more than inferences that do not require counterexamples (Kroger, Nystrom, Cohen, & Johnson-Laird, 2008).

Counterfactual Reasoning

Models can contain information to represent epistemic elements of beliefs, such as their counterfactuality (Byrne, 2005, 2007). Counterfactual thoughts, "if only I had gone home by my usual route I wouldn't have had an accident" are pervasive in everyday thinking (Dixon & Byrne, 2011; Kahneman & Tversky, 1982; McEleney & Byrne, 2006). When people read a counterfactual conditional "if there *had been* a lily in the vase there *would have been* a rose" they think about two possibilities from the outset (Byrne & Tasso, 1999). They consider the conjecture: "there was a lily and there was a rose" and also the presupposed facts: "there was no lily and there was no rose," and they keep track of the epistemic status of one as an imagined possibility and the other as a factual possibility (Johnson-Laird & Byrne, 1991). They are primed to read a negative conjunction "there was no lily and there was no rose" faster when they first read a counterfactual conditional compared to when they first read an indicative conditional; they read quickly the affirmative conjunction "there was a lily and there was a rose" whether they are primed by either the counterfactual or the indicative conditional (De Vega, Urrutia, & Riffo, 2007; Santamaria, Espino, & Byrne, 2005). Studies that track where participants' eyes focus when they read counterfactuals show that real-world violations, for example, "owners could feed their cats carrots" are not neutralized by a counterfactual context, for example, "if cats were vegetarians," indicating that people keep in mind both models (Ferguson & Stanford, 2007). People simulate the counterfactual situation as much as the factual situation, so that physical actions that compete with the counterfactual action delay processing just as much as ones that compete with the factual action (De Vega & Urrutia, 2011).

People judge that someone who utters the counterfactual meant to convey "there was no lily" and "there was no rose" (Thompson & Byrne, 2002), and they mistakenly believe they were told so when they are given a surprise memory task (Fillenbaum, 1974). The negative inferences such as *modus tollens* are made more readily from a counterfactual compared to an indicative conditional, whereas the affirmative inferences such as *modus ponens* are made with equal frequency (Byrne & Tasso, 1999; Quelhas & Byrne, 2003). The inferences people make from counterfactuals are influenced by linguistic form, for example, "even if" and "only if" (Egan, Garcia-Madruga, & Byrne, 2009; Moreno-Rios, Garcia-Madruga, & Byrne, 2008). Counterfactual threats,

for example, "if you had hit your brother I would have grounded you" are interpreted as threatening for the future, whereas counterfactual promises "if you had mown the grass I would have given you 10 euro" are not (Egan & Byrne, 2012).

KEY ISSUES FOR FUTURE RESEARCH

Extensions of the model theory to explain different kinds of thinking are an important development. For example, a recent extension of the theory to account for moral judgments distinguishes between conscious deliberative reasoning about moral matters and unconscious intuitive moral judgments (Bucciarelli *et al*., 2008). Other extensions of the theory, for example, to explain problem solving or the nature of explanations, clarify the assumptions that lead people to construct or eliminate possibilities (e.g., Khemlani & Johnson-Laird, 2012; Lee & Johnson-Laird, 2012).

The model theory is an alternative to views based on probability (Evans & Over, 2004; Oaksford & Chater, 2007) or mental inference rules, either abstract or content-sensitive (Braine & O'Brien, 1998; Cheng & Holyoak, 1985; Cosmides, Tooby, Fiddick, & Bryant, 2005; Rips, 1994). Comparisons of the predictions of the alternative theories remain important, for example, a recent meta-analysis systematically compares seven alternative theories of syllogistic inference against the existing empirical evidence (Khemlani & Johnson-Laird, 2012).

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